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The Estimation of Clear Sky Global Horizontal Irradiance at the Equator

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Abstract

We analyse Singapore global horizontal irradiance (GHI) measurements to estimate clear sky GHI in the equator region. The data consists of a one-year period of clear sky GHI at three solar irradiance monitoring stations in Singapore, namely, First Zero Energy House in Singapore (1.3094°N, 103.9160°E) located in the east of the country, Solar Energy Research Institute of Singapore (1.3007°N, 103.7718°E) in the mid-west, and Nanyang Technology University Intelligence Systems Center (1.3436°N, 103.6792°E) in the west. Several empirical clear sky models are considered for a Singapore case study. An regression method is proposed to parameterize the model of choice for Singapore's measured GHI. The developed model is validated using GHI measurements from difference stations over different time periods.

Keywords: Clear sky global solar irradiance

1. Introduction

Knowledge of the clear sky global solar irradiance (GHI) (the maximum solar radiation at a specific time and place on the earth's surface when no cloud is present) reaching the ground is a key parameter in the field of solar radiation modeling and systems evaluation [1].

One of its key applications of clear sky models is to predict PV array power output, a process that requires continuous datasets with diurnal and seasonal trends removed. Procedures to interpolate missing data and GHI trend removal using Fourier analysis are made possible with realistic clear sky GHI models.

Many authors have developed empirical equations to estimate the clear sky GHI [2, 3, 4, 5, 6, 7, 8] while others adopt a physical approach [9, 10, 11, 12]. When local measurements are made and the relative

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performance of these models is assessed [13, 14, 15], it transpires that different approaches are optimal in different geographical locations.

Empirical models are generally the simplest, with model parameters determined using the regression of local clear sky GHI. The values of empirical model parameters differ for different datasets, e.g. at different geographical locations or for different time periods. Physical models have the advantages of generality and accuracy, but they require more input parameters such as column ozone, column precipitable water, aerosol optical depth and other atmospheric transmittances.

Recently, a semi-empirical model for estimation of clear sky GHI has been developed by Janjai *et al.* [16]. They modified the key finding of reference [8] by introducing five physical parameters into the model, namely, the Angstrom turbidity coefficient, Angstrom wavelength exponent, precipitable water, total column ozone and eccentricity. Eccentricity, which describes the Earth's orbit around the sun, does not require any measurements. The other four parameters are obtained directly or indirectly from the Aerosol Robotic Network (AERONET) [16], a network of ground-based sun photometers which measure atmospheric aerosol properties. Additionally, sky cameras are employed to identify the clear sky situation. These measurement procedures increase the complexity of the clear sky model.

The clear sky GHI serves as an upper bound for accurately measured GHI. We note that this is a compromise to optimise accuracy against simplicity: reflections from clouds can result in instantaneous measurements greater than clear sky predictions. Thus we employ a simple model, modified from reference [8], to estimate the clear sky GHI using only two inputs, namely, the day number and the zenith angle.

This paper represents preliminary results of a study that aims to produce high temporal and spatial resolution GHI forecasts for tropical regions.

2. Measurements

GHI data is available through several databases such as the National Solar Radiation Database (NSRDB) and the Measurement and Instrumentation Data Center (MIDC) [17] in the USA. These data are recoded hourly; the stations are usually far apart (compared to the distances among the Singapore sites used in this work).

The resolution of one hour filters out GHI variations (ramp rates) with high frequencies. Figure 1 illustrates the difference in ramp rates between hourly data and one or five minute data, where more variations are seen than in the hourly series. Capturing these high frequency GHI variations is the motivation for measurements of highly time-resolved data in Singapore.

Three GHI measurement sites are used in this work: First Zero Energy House in Singapore (FZEHS), Solar Energy Research Institute of Singapore (SERIS) and Nanyang Technology University Intelligence Systems Center (NISC). The temporal resolution of SERIS and NISC is one minute and FZEHS is five minute. Although one minute data shows more information, to utilise data of all three measurement sites, only five minute data is used in this study.

The geographic relationship of station locations is important for spatial-temporal analyses: reference [18] shows that the Pearson's correlation coefficient of GHI between sites increases with geographic proximity. Figure 2 shows the geographical location of the three sites: FZEHS, SERIS and NISC. The distance between FZEHS and SERIS is 23km and 15km between SERIS and NISC.

High temporal resolution and the geographic proximity of Singapore GHI measurements allow us to perform efficient solar radiation modelling and evaluation through spatial-temporal analyses.

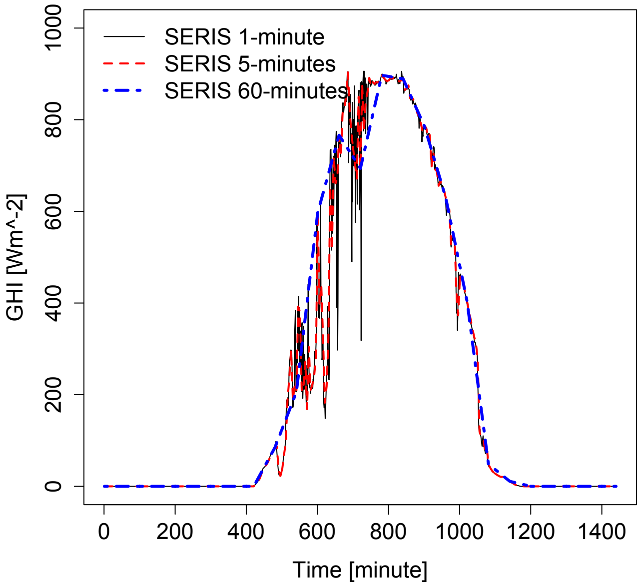

Fig. 1: Comparison of original one minute GHI data, with five and sixty minute data for SERIS on 2011 July 5.

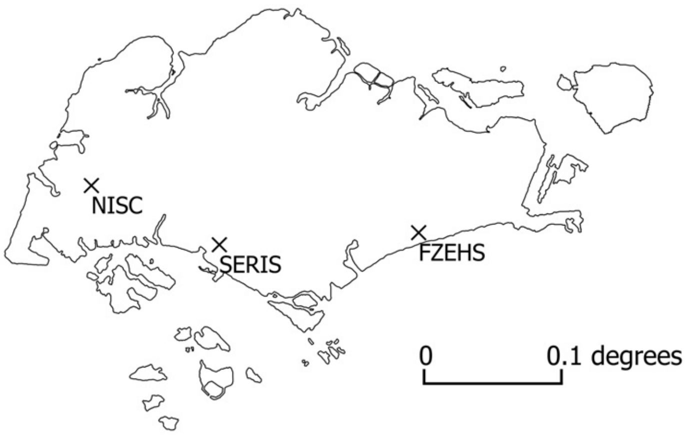

Fig. 2: The solar monitoring stations used in this study on map of Singapore: First Zero Energy House in Singapore (FZEHS), Solar Energy Research Institute of Singapore (SERIS), and Nanyang Technology University Intelligence Systems Center (NISC).

3. Estimation of Clear Sky GHI

We aim for the simplest clear sky GHI model with adequate accuracy. We select five empirical models from various sources [2, 3, 5, 6, 7, 8]. The zenith angle (θ_z) is the only input parameter for all five models: we calculate θ_z using NREL's Solar Positioning Algorithm (SPA) [19]. A C program was written to implement SPA to generate the per-minute zenith angle over a period of one year. Figure 3 shows the comparison of the performance of the five empirical models against five minute data for SERIS on 2011 August 5. The models are listed in Appendix A.

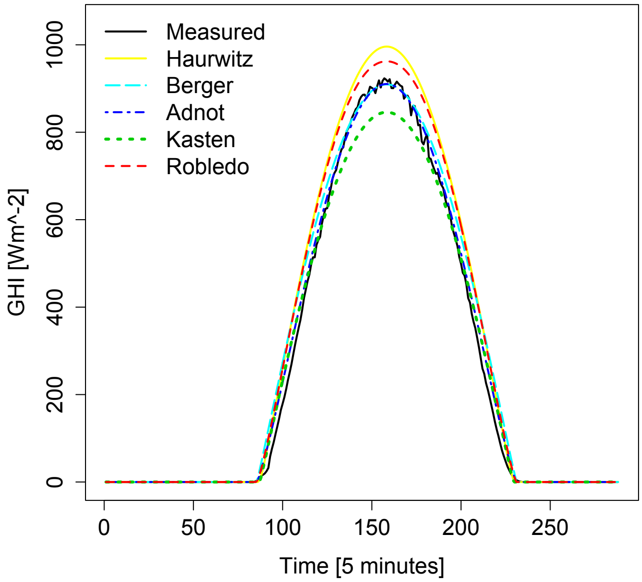

Fig. 3: Comparison of the performance of the five empirical models (see Appendix A) against five minute data for SERIS on 2011 August 5

3.1. Model Selection

Singapore had a clear sky situation during entire day of 2011 August 5; the frequency of occurrence of such days is estimate to be once every two years. As shown in Figure 3, the Haurwitz model and the Robledo-Soler model overestimate the GHI on that day while the Kasten model has an under estimation. The Berger model and the Adnot model fit SERIS data relatively well in terms of both magnitude and shape.

As both over- and under-estimation may cause inaccurate prediction in PV system output, we select the Adnot model as it most precisely reflects the possible clear sky GHI in Singapore. Table 1 records Pearson's correlation coefficient between the five individual models and SERIS data. The Adnot model has the highest Pearson's correlation coefficient of 0.9987 which agrees with our graphical observations.

Table 1: The Pearson's correlation coefficient with measured GHI using various models.

Model	Pearson's correlation coefficient
Haurwitz	0.9980984
Berger	0.9955589
Adnot	**0.9987115**
Kasten	0.9973335
Robledo	0.9974868

3.2. Model Modification

In the previous section where various empirical models are compared, we find that the Adnot model gives the best fit for SERIS data. The Adnot model was developed using data collected in France; it was not optimised for GHI at the equator. Therefore, we modify this model as follows:

The clear sky GHI is expressed in the Adnot model as follows:

$$G_c = a(\cos\theta_z)^b \tag{1}$$

where a and b are regression parameters, equal to 951.39 and 1.15 respectively. G_c is the clear sky GHI in Wm^{-2}. The clear sky GHI described by the Adnot model is a univariate function of zenith angle.

In a forthcoming paper, we show that by adjusting the value of a and b; including more parameters, we can derive a sufficiently accurate clear sky GHI model for Singapore. The modified estimation of clear sky GHI is governed by:

$$G_c = aE_0 I_{sc}(\cos\theta_z)^b e^{c(90-\theta_z)} \tag{2}$$

where E_0 is eccentricity correction factor of earth; I_{sc} is solar constant (1366.1 Wm^{-2}). Values of a and b are determined by the local measured GHI. The exponential term is a simple empirical representation of complex physics of radiative transfer. It is very similar to a quantity called pseudo-optical depth.

We define a clear sky condition by calculating clearness index ε', to select data for use in model parameter fitting. ε' is defined in [20]:

$$\varepsilon' = [(D_h + D_n)/D_h + \kappa Z^3]/[1 + \kappa Z^3] \tag{3}$$

where D_h is diffuse horizontal irradiance and D_n is direct normal irradiance both in Wm^{-2}. κ is a constant equal to 1.041, and Z is zenith angle in radians. We propose that a clear sky situation prevails in Singapore if $\varepsilon' > 3.5$.

The modified clear sky GHI is:

$$G_c = 0.8277 E_0 I_{sc}(\cos\theta_z)^{1.3644} e^{-0.0013\times(90-\theta_z)} \tag{4}$$

Figure 4 shows the comparison of the modified model with 5 mins data for SERIS on 2011 August 5. The Person's correlation coefficient of our modified model is 0.9997323, which is higher than all the other values shown in Table 1.

3.3. Model Validation

We benchmark our clear sky model using the "true" GHI measured at the FZEHS during year 2010. Figure5 shows the scatter plot of the measured clear sky GHI and the predicted clear sky GHI during year 2010.

4. Conclusions

Three sets of Singapore GHI data have obtained and used to develop a local clear sky model.

A simple empirical model for clear sky GHI in Singapore is developed with five parameters: I_{sc}, the extraterrestrial solar irradiance, E_0, the eccentricity correction factor, together with the cosine of zenith angle to provide a seasonal variation and two model parameters. The model parameters a and b are determined by local GHI measurement, in this case, the Singapore data, to approximate various atmosphere transmission mechanisms. The model is simplistic when compared to a physical model but it is easy to compute and

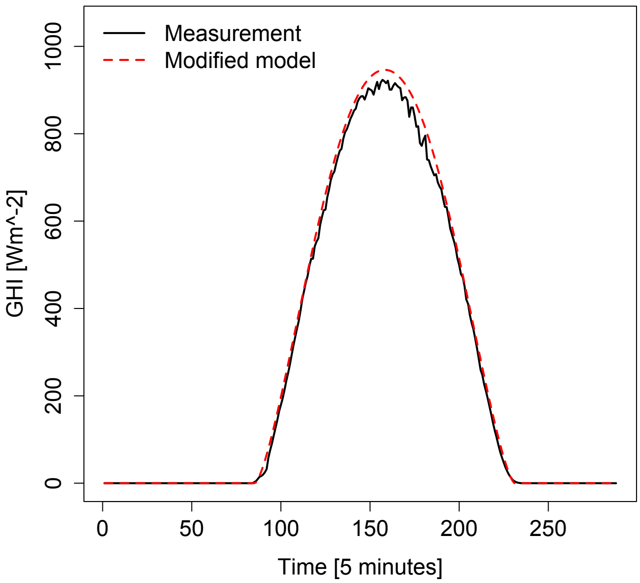

Fig. 4: Comparison of the modified model with 5 mins data for SERIS on 2011 August 5.

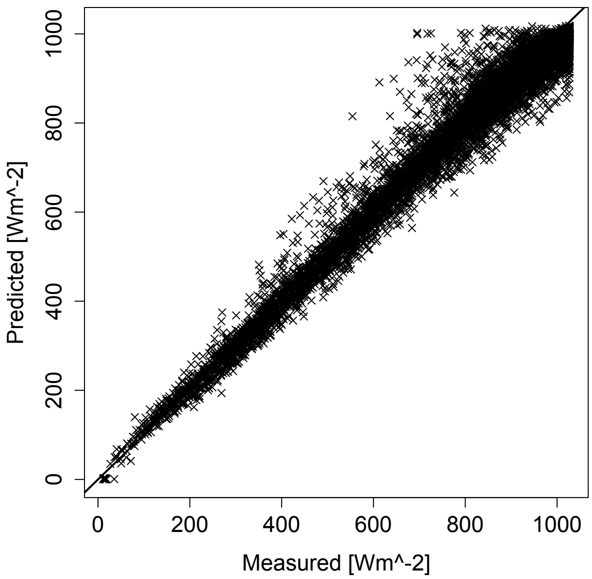

Fig. 5: Performance of the modified clear sky model for all clear sky situation during year 2010.

flexible: one can iterate the model parameters using local data sets.

We intend to utilize the developed model in our future work on performing missing data generation and

GHI trend removal using Fourier analysis.

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Appendix A. Empirical Models for Clear Sky GHI Used for Comparison

The Haurwitz model [2, 3]:

$$G_c = 1098[\cos\theta_z e^{-0.057/\cos\theta_z}]$$

The Berger-Duffie model [6]:

$$G_c = 1350[0.70\cos\theta_z]$$

The Adnot-Bourges-Campana-Gicquel model [6]:

$$G_c = 951.39\cos^{1.15}(\theta_z)$$

The Kasten-Czeplak model [7]:

$$G_c = 910\cos\theta_z - 30$$

The Robledo-Soler model [8]:

$$G_c = 1159.24(\cos\theta_z)^{1.179}e^{-0.0019(90-\theta_z)}$$